Joint Centre for Mesoscale Meteorology, Reading, UK

The mystery of striated cloud heads in satellite imagery

K. A. Browning
R. S. Dixon
G. J. Shutts

Internal Report No. 116
NWP Technical Report No. 312

April 2000

Met Office Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
www.metoffice.com

Designed and produced by the Met Office © Crown copyright 2001 01/0240 The Met Office logo is a registered trademark.

The mystery of striated cloud heads in satellite imagery

R. S. Dixon, K. A. Browning and G. J. Shutts

Submitted to Atmospheric Science Letters

April 2000

1 Introduction

Figure 1 shows an example of a cloud head over the mid-Atlantic as seen in infra-red imagery from the satellite Meteosat. The cloud head is the overall cloud system occupying much of the left-hand (western) half of the figure. The larger cloud system with colder (higher) cloud tops, occupying the right-hand (eastern) half of the figure is the polar front cloud band. The term cloud head was first used by Böttger *et al.* (1975) who recognized it as it as a feature that frequently precedes a period of rapid cyclonic development. The relationship of cloud heads to the overall structure and dynamics of the associated cyclone is described in Browning and Roberts (1994) and Bader *et al.* (1995). Cloud heads have been shown to be prominent features of several notable cyclones, a memorable one in north-west Europe being the Great Storm of October 1987 (Shutts (1990)). The identification of cloud heads in satellite imagery now plays an important role in operational forecasting practice (e.g. Young and Grahame (1999)). The particular feature of the cloud head in

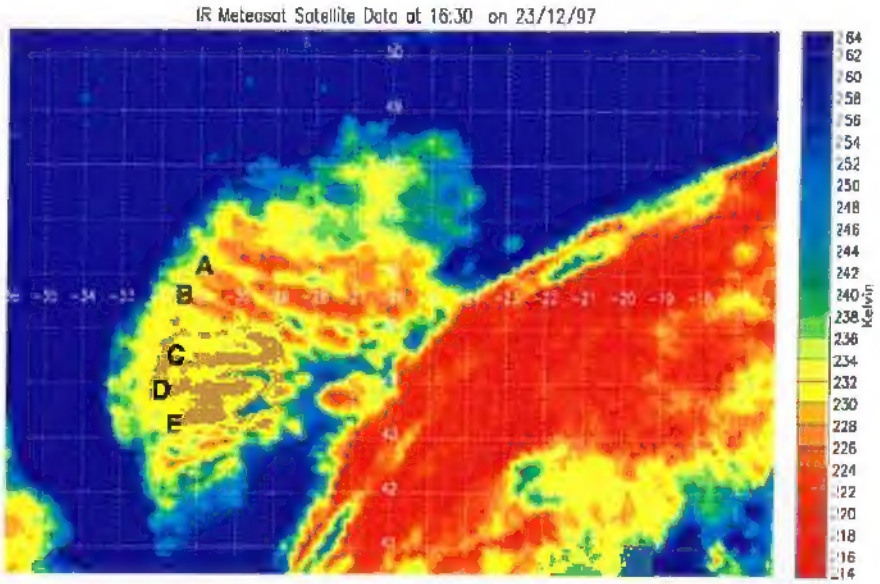

Figure 1: *False colour infra-red Meteosat image at 1630UTC on 23rd December 1997. A, B, C, D and E show the positions of striations as they move through the cloud head. [For an animated image, refer to the electronic version of this article in Atmospheric Science Letters.]*

figure 1 that will be stressed in the present study is the series of striations in cloud-top height (temperature). Striations in cloud heads were first mentioned by Shutts (1990)

and Norris and Young (1991); the striations described by Shutts had a characteristic wavelength of 10km whereas those described by Norris and Young, like those in the present study, are much longer. Five of the striations are labelled A, B, C, D and E and four can be tracked throughout the 2-hour sequence of images in figure 1. They extend radially outward across the width of the cloud head, roughly at right angles to the outer boundaries of both the cloud head and the band of higher polar-front cloud to the east.

The striations on this, as on other occasions, are not just fleeting features in the cloud head structure: indeed some individual striations could be followed for over 5 hours. By viewing the imagery in a frame of reference moving with the cloud head, the individual striations can be seen forming at the upwind (south-western) end of the cloud head, then moving through the cloud head and decaying at its downwind (north-eastern) end. Individual striations travel at a velocity of about 50m/s relative to the ground. They have a wavelength of about 60km and their maximum length and crest-to-trough amplitude are 250km and approximately 1.4km, respectively. Similar striations have been observed in many lows by Feren (1995) who regarded them as an indication of strong winds and rapid deepening; of the 37 lows that exhibited what Feren called a "striated delta" cloud structure, 75% were associated with at least gale-force winds and most exhibited a 12-hour period of explosive deepening. Gales and explosive deepening also characterised the case shown in figure 1: this is the storm that crossed the United Kingdom on 24th December 1997, accompanied by surface winds gusting in some places to in excess of 40m/s. The cyclone with which the cloud head was associated deepened by 23mb in 12 hours during its period of most rapid development. In the next section we present a more detailed analysis of another example of cloud-head striations and then in section 3 we discuss possible mechanisms for their generation.

2 Case Study of cloud-head striations on 25th December 1998

The event shown in figure 2 occurred over the north Atlantic during Christmas Day in 1998. A feature of this case is that six partially overlapping cloud heads exist simultaneously. These are marked 1 to 6 in figure 3. Some of the cloud heads again show striations in the cloud tops although the striations are only about half the length of those in the previous example in figure 1. As in the previous example, the striations can be tracked as they progress through the cloud head. Figure 2 shows an animation between 1200UTC and 1530UTC, with imagery every 30 minutes. We concentrate our attention on the striations within Cloud Head 5. Five striations (A to E) have been analysed, the ends of which are annotated within figures 2 and 3 (note that the labels are at the south-eastern ends of the

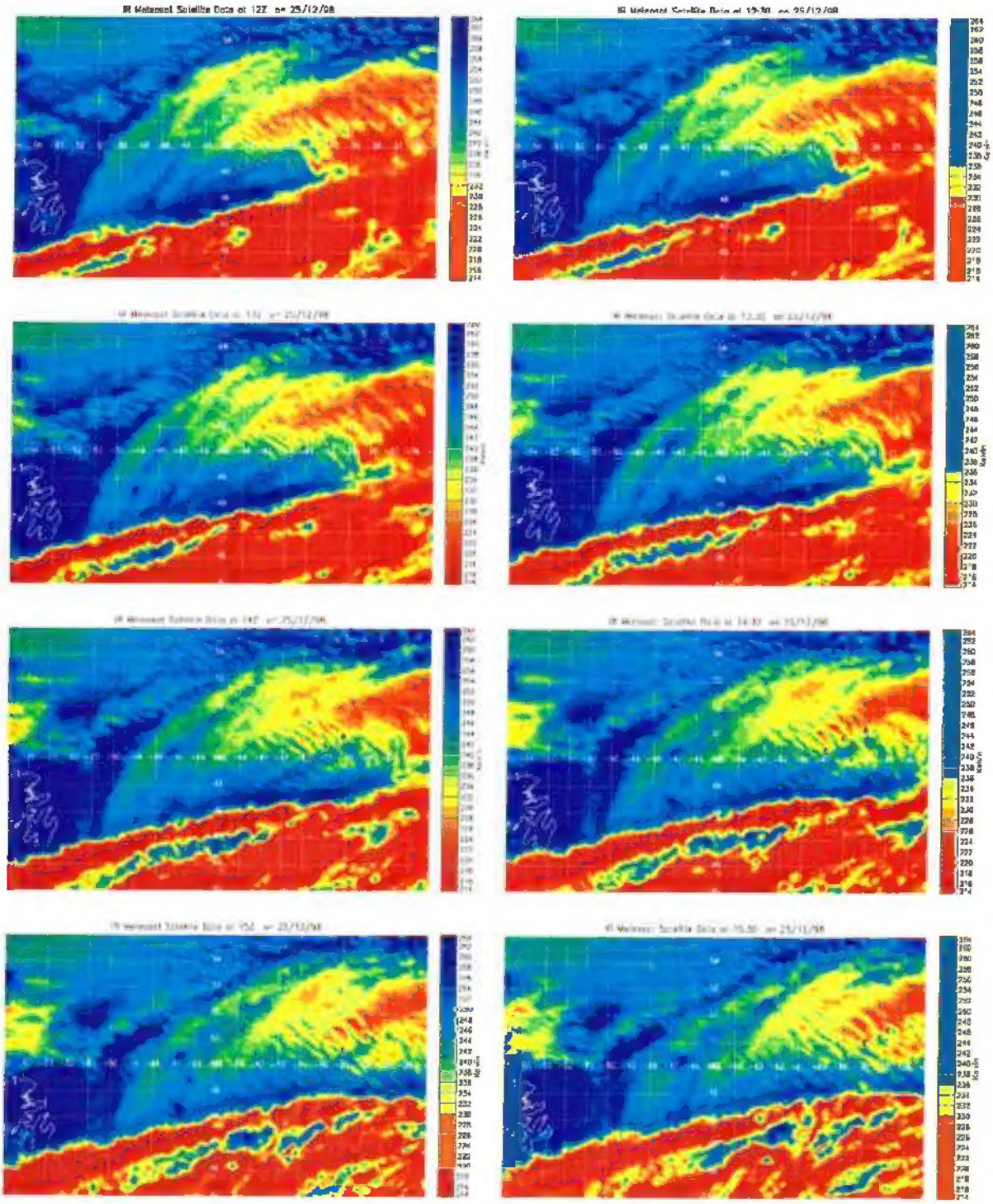

Figure 2: *Half-hourly infrared Meteosat imagery from 1200UTC to 1530UTC on 25th December 1998. A, B, C, D, E label striations as they advance through the cloud head but B and D are labelled only at the initial time. This lettering is referred to in later figures.*

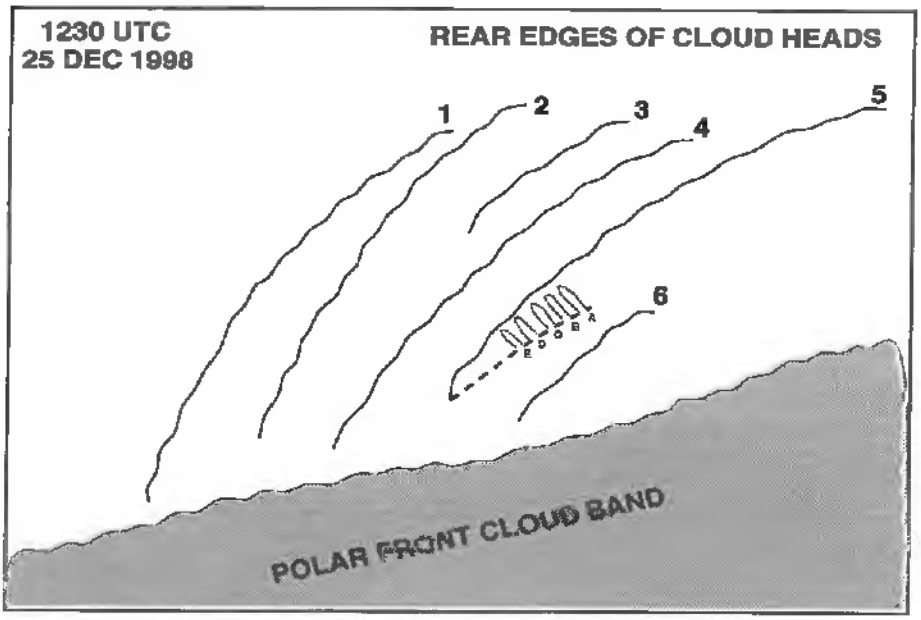

Figure 3: *Sketch of 1230UTC image from figure 2 showing the polar front cloud band (shaded) and the rear edges of the six partially overlapping cloud heads. The cloud striations A,B,C,D and E analysed in this study were associated with Cloud Head 5 and are shown. The dashed line connecting the south-eastern ends of these striations, extending to the south-western tip of Cloud Head 5, denotes the band of line convection that was observed along the south-eastern edge of Cloud Head 5.*

striations rather than the north-western ends as was the case in figure 1).

At 1300UTC, the sun's angle was such that visible imagery from Meteosat (not shown) was able to reveal the surface cold front associated with Cloud Head 5 as a line of bright cloud tops that characterise line convection at the surface (as in figure 1 of Browning and Harrold (1970)).

Several properties of the striations can be defined, as shown in the schematic in figure 4. Table 1 shows characteristic values for these variables. The speed of travel of the striations varies from striation to striation and with time. The striations travel most slowly in their early stages of development. Average speed varies from approximately 48m/s for Striation A to 41m/s for Striation E. As in the case described in the introduction, the striations form at the upwind (south-western) end of the cloud heads and then move through the cloud heads to decay at their downwind end. The tops of the crests of the striations tend to become rather flattened with time. The flat top of Striation C is about 15km wide at 1200UTC and is 50km wide by 1530UTC. The average horizontal wavelength of the striations increases with time from 30 to 55km. The wavelength also increases from Striation E through to Striation A at any given time.

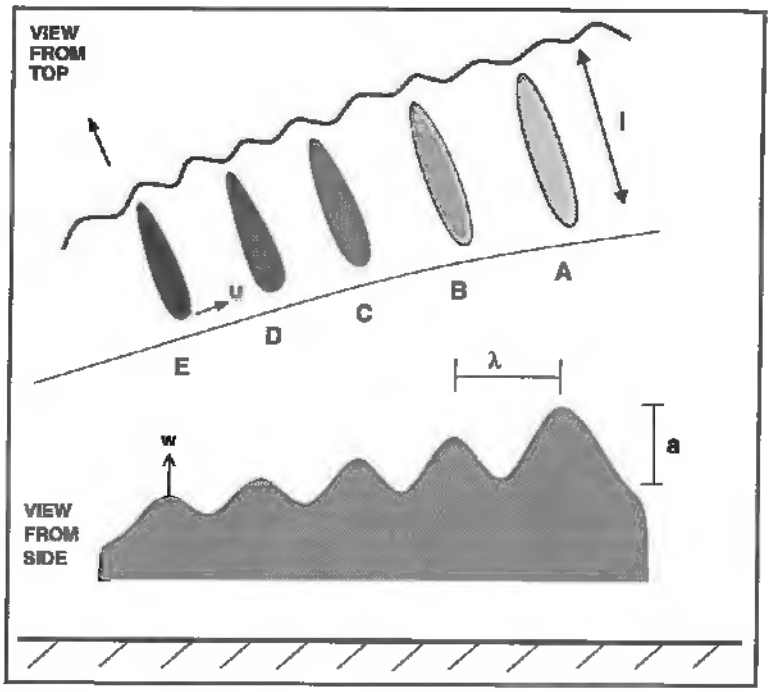

Figure 4: *Schematic representation of the cloud striations A,B,C,D and E associated with Cloud Head 5 as viewed from the top and the side. The striations A, C and E have been analysed to determine their length l, cloud-top height h, along-cloud-head velocity u, cloud-top rate of ascent w, characteristic horizontal wavelength λ and crest-to-trough amplitude a.*

Figure 6 shows the thermodynamic structure in the vicinity of the striations as determined from the 1200UTC operational analysis of the UK Met. Office Limited Area Model (LAM). The X in figure 5 shows the position of this temperature profile in relation to the model's own representation of the field of cloud-top temperature. Comparison of figure 5 with figure 2 shows that the model, whilst not resolving the individual striations or indeed details of the multiple cloud-head structure, successfully represents the overall structure of the cloud-head region, albeit with a positional error (the model's cloud head is about 150km too far north-northeast but this has been taken into account in finding the position X in the model that is relevant to the observed striations).

According to figure 6, the cloud head is associated with an exceptionally strong and deep frontal zone extending between 800 and 500mb. Across this layer the potential temperature increases by as much as 23K, whilst the south-westerly winds increase from 5 to 65 knots (about 2 to 32m/s). The shear in the model is orientated almost parallel to the elongated cloud head and its associated frontal zone. The wind continues to increase above 500mb, reaching 100 knots (50m/s) in the dry air at 350mb. Between this dry air

Variable	Summary of Characteristics
wavelength λ	30km (at 1200UTC) to 55km (at 1500UTC) averaged over all the striations
crest-to-trough amplitude a	Typically 1km, maximum of approx. 2km (e.g. C at 1400UTC)
length l	Between 70km (e.g. E at 1200UTC) and 140km (C at 1530UTC)
ground-relative velocity u	A: 41m/s (1200UTC) to 52m/s (1400UTC), average=48m/s C: 39m/s (1200UTC) to 55m/s (1430UTC), average=46m/s E: 33m/s (1200UTC) to 47m/s (1430UTC), average=41m/s
cloud-top height h	A: 6.5km at 1200UTC to 9km at 1430UTC C: 6.2km at 1200UTC to 9km at 1530UTC E: 5.5km at 1200UTC to 7.7km at 1530UTC
vertical velocity w	Approx. 16cm/s averaged over 3.5 hours for A,C and E.

Table 1: Summary of characteristics of striations within Cloud Head 5 in figure 2 (see figure 4 for definitions).

and the essentially saturated air in the frontal zone, there is a layer of almost constant wet-bulb potential temperature θ_w, with a slight decrease in relative humidity from 500 and 420mb. The temperature profile in figure 6 is representative of the developing striations towards the upwind end of the train of striations (i.e. Striation D at 1230UTC (figure 3)). In this region, the observed temperatures at the crests and troughs are typically 233K and 243K (figure 2). This is consistent with the cloud-top striations being situated within the constant-θ_w layer between 500 and 420mb, as labelled in figure 6, and gives a typical cloud-top height, h, of 5.6km and a crest-trough amplitude of approximately 1.4km. Figure 2 suggests some degree of coherence in the striations within adjacent cloud heads. Since the flows associated with the adjacent cloud heads are partally overlapping, this would not be surprising. However, the wavelengths of the striations in neighbouring cloud heads are not identical, so there is inevitably also a degree of mismatch between their striations.

3 Discussion

Here we consider candidate mechanisms that may have been responsible for the striations within the cloud heads.

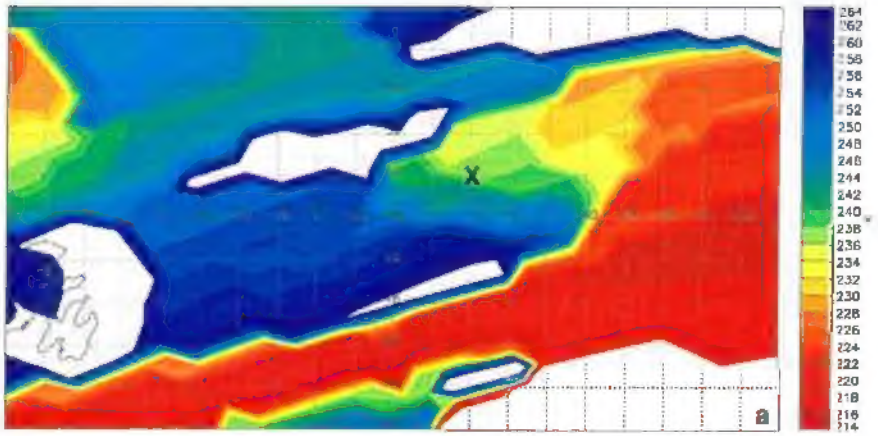

Figure 5: *Pseudo infra-red image for the LAM analysis at 1200UTC. Cross shows the position of the tephigram in figure 6.*

1 - Conditional symmetric instability (CSI)

Bennetts and Hoskins (1979) showed that mesoscale bands of ascent within frontal systems may be due to the release of CSI. This manifests itself as rolls along the thermal wind. The LAM data suggest that the thermal gradients in this example are aligned WSW-ENE and thus any bands due to CSI should be oriented in this direction. The striations in this case are, however, orientated NNW-SSE and cannot be attributed to CSI. On the other hand, it is possible that the multiplicity of observed cloud heads, which is symptomatic of a multiplicity of transverse circulations, may be due to CSI: certainly values of Slantwise Convective Available Potential Energy (SCAPE) as high as 2500J/kg were diagnosed from the NWP model on this occasion (Dixon (2000)). The failure of the model to fully resolve the multiple cloud heads can be attributed to the coarseness of its (50km) grid (Persson and Warner (1993)).

2 - Line convection

As mentioned in section 2, the visible imagery indicated the existence of line convection at the south-eastern ends of the striations. Although the resolution of the imagery is insufficient to resolve the fine structure of the line convection, James and Browning (1979) and Hobbs and Biswas (1979) have shown that the surface cold-frontal ascent at line convection tends to be split up into cores of stronger ascent along the length of the front. These cores, or line elements, vary in length but a length of several tens of kilometres would not be unusual. Satellite imagery in Dixon (2000) showed how these convective cores might feed plumes of slantwise ascent. As they rise behind the front, these plumes are drawn out

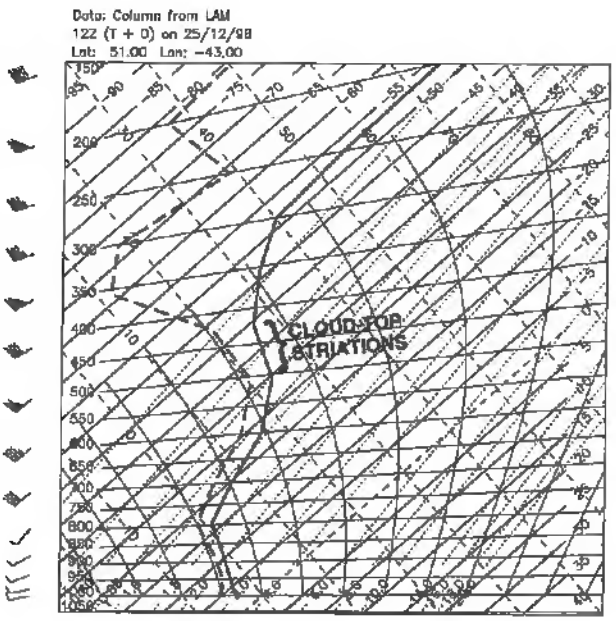

Figure 6: *a) Tephigram from the model at the point shown in the previous figure. Each half, full and solid wind barb in b) corresponds to a windspeed of 5, 10 and 50 knots, respectively.*

in the along-front direction by the background geostrophic vertical shear . As suggested by satellite observations in the study by Dixon, this causes the plumes to be orientated at angles approximately 30 degrees to the thermal wind. The striations in the present study are at 90 degrees to the thermal wind, which suggests that they are not due to plumes emanating from the line convection.

3 - Convective rolls

The organisation of boundary-layer convection into long roll clouds aligned approximately in the direction of the mean wind shear is commonly observed in satellite imagery (e.g. in the polar air as it flows off an ice sheet over relatively warm seas). If the air ascending slantwise is conditionally unstable, as it might be in the layer between 500mb and 420mb in figure 5, and this instability is released during uplift, then similar convective rolls could result at these upper levels. As time goes on, the tops of the convective rolls would reach the base of the overlying stable layer and could be expected to flatten, as observed in this case.

This interpretation of the cloud striations would hold only if the wind shear were dominated by the ageostrophic, slantwise-ascending flow. However, in this case, at least in the model, the shear is dominated by the thermal wind shear which is normal to the orientation of the striations. It may be, however, that the smallness of the wind-component

in the cross-frontal plane, shown by the wind barbs in figure 6, is because the model, as mentioned above, is not able to resolve the augmentation of the frontal circulation by symmetric instability.

The separation of convective cloud rolls is proportional to the depth of the unstable layer and for boundary-layer rolls would be typically about 10km (e.g. Wallace and Hobbs (1977)). Whilst this separation is not inconsistent with the separation of the striations found in the October 1987 storm (Shutts (1990)), it is too small to account in a straightforward way for the observations here. On the other hand, it appears that the depth of a convecting layer is not the only factor in determining the spacing of cloud updraughts. Mesoscale cellular convection over the ocean frequently has cell diameters of 40km in a convecting layer 1 to 2km deep. There is evidence from numerical modelling studies (e.g. Fiedler (1990)) that convection cells can grow in horizontal extent by cell merging, particularly for three-dimensional cell organisation. It may be that the increase in striation separation as time progresses is a manifestation of a similar scale-broadening process.

4 - Kelvin-Helmholtz Instability (KHI)

Another possibility is that the striations may be related to KH billows occurring within the strongly sheared frontal zone. In the model, the main component of the shear appears to be due to the thermal wind. The attraction of invoking KHI is that the orientation of the observed striations is consistent with the expected orientation of any billows in this zone (although, as noted above, this assumes that the flow pattern in the model is broadly correct). A necessary condition for KHI is that the Richardson number (Ri) is less than 0.25 (Miles and Howard (1964)). For a sheared layer of finite thickness Δ, the fastest growing wavelength for billows is given by Miles and Howard as $\lambda = 7.5\ \Delta\ z$. Inspection of the vertical profile in figure 6 shows that there is, at most, a 4km deep frontal zone. If the instability were to exist over the whole of this depth (most unlikely) then the instability would be manifest with a wavelength of 30km, which is too small compared to the wavelengths shown in table 1. Indeed, inspection of the moist Richardson number in the UK Meteorological Office's Limited Area Model suggests that values of Ri fall below 1 only over a layer about 1km thick. Thus KHI does not account for the observed striations.

5 - Spike Clouds

Scorer (1997) has identified a banded cloud structure that commonly occurs in the upper part of frontal zones and refers to these as 'spike clouds'. They frequently appear as sharp inverted-V patterns pointing up the frontal surface - often with their pointed ends close to the periphery of a cirrus cloud shield. The separation between individual spikes is typically 30 to 40km, i.e. similar to that of the striations shown in this paper. It is difficult to say whether or not the underlying dynamical mechanism for these clouds may

be the same as for the present striations, though it should be noted that they both grow in environments of weak slantwise stability. Scorer himself only goes as far as relating the generation mechanism to the inherent instability of three-dimensional vortex tubes. The tendency of cirrus fallstreaks to lie normal to the thermal wind shear was discussed by Ludlam (1980). From careful visual observations he concluded that these cirrus-fallstreak cloud systems lay within layers of intense ageostrophic shear resulting from the adjustment of jet streaks. The ageostrophic shear would therefore appear to be the main contributor to the total shear in Ludlam's study and falling ice crystals would trail along the total shear vector at right angles to the flow. In the present study, however, the wind shear is dominated by the thermal wind component unless, as described above, the model is underestimating the transverse circulation due to its inability to resolve the release of CSI.

6 - Gravity Waves

The spatially-periodic form of the striations in our study is reminiscent of trapped lee waves, though with horizontal wavelengths somewhat larger than ones generated by mountains,. The horizontal energy propagation necessary to allow such a wavetrain would be possible only if wave energy were effectively trapped near the frontal surface. How this might be achieved when the striations appear to be travelling with a speed not greatly different from that of the flow at their level is hard to see and represents the principal objection to this dynamical mechanism. It is also difficult to understand why trapped gravity waves would become aligned transverse to the front when the most obvious forcing mechanism is the line convection itself. Feren (1995) suggests the possibility that the waves are associated with geostrophic adjustment near upper jet streaks, i.e. the Lighthill radiation mechanism discussed in a shallow-water equation context by Ford (1994). The striations observed by Shutts (1990) were seen to emanate from line convection in the lower troposphere, becoming indistinct in the upper troposphere, and therefore making this process an unlikely dynamical candidate. Nevertheless the possibility that a quasi-balanced frontal surface being drawn into a vortex could excite gravity waves is interesting.

4 Conclusions

The discussions of possible mechanisms in this study are based on an NWP analysis which, although capable of representing the existence of the cloud head with which the striations are associated, cannot be relied upon to represent critical details. The balance of evidence is arguably in favour of the striations being due to convective rolls occurring above a frontal zone in the presence of a strong ageostrophic circulation grossly under-resolved by the model. There were no in situ observations of the wind and thermal structure in this or, as far as we know, any other striated cloud head and, until there are, their cause

will remain a mystery. The cases studied in this paper are some of the clearest examples of striated cloud heads we have seen and our purpose in showing them is to stimulate the search for better observations and theories. Striated cloud heads accompany some of the most extreme cases of rapid cyclogenesis and so this is a mystery of some practical significance.

References

Bader, M. J., Forbes, G. S., Grant, J. R., Lilley, R. B. E., and Waters, A. J. (1995). *Images in Weather Forecasting.* Oxford University Press.

Bennetts, D. A. and Hoskins, B. J. (1979). Conditional symmetric instability - a possible explanation for frontal rainbands. *Quart. J. Roy. Meteor. Soc.*, **105**, 945–962.

Böttger, H., Eckhardt, M., and Katergiannakis, U. (1975). Forecasting extratropical storms with hurricane intensity using satellite information. *J. Appl. Meteor.*, **14**, 1259 1265.

Browning, K. A. and Harrold, T. W. (1970). Air motion and precipitation growth at a cold front. *Quart. J. Roy. Meteor. Soc.*, **96**, 369–389.

Browning, K. A. and Roberts, N. M. (1994). Structure of a frontal cyclone. *Quart. J. Roy. Meteor. Soc.*, **120**, 1535–1557.

Dixon, R. S. (2000). Diagnostic studies of symmetric instability. *Ph.D Thesis.*

Feren, G. (1995). The striated-delta cloud system - a satellite imagery precursor to major cyclogenesis in the Eastern Australian-Western Tasman Sea region. *Wea. Forecasting*, **10**, 286–309.

Fiedler, B. H. (1990). Transitions to broad cells in a nonlinear thermal convection system. *Geophys. and Astrophys. Fluid*, **50**, 195–201.

Ford, R. (1994). Gravity wave radiation from vortex trains in rotating shallow water. *J. Fluid Mech.*, **281**, 81–118.

Hobbs, P. V. and Biswas, K. R. (1979). The cellular structure of narrow cold-frontal rainbands. *Quart. J. Roy. Meteor. Soc.*, **105**, 371–382.

James, P. K. and Browning, K. A. (1979). Mesoscale structure of line convection at surface cold fronts. *Quart. J. Roy. Meteor. Soc.*, **105**, 371–382.

Ludlam, F. H. (1980). *Clouds and Storms.* The Pennsylvania State University Press, University Park and London.

Miles, J. W. and Howard, L. N. (1964). Note on a heterogeneous shear flow. *J. Fluid Mech.*, **20**, 331 336.

Norris, J. and Young, M. V. (1991). Satellite photographs, 2 February 1991 at 1533 UTC. *Met. Mag.*, **120**, 115–116.

Persson, P. O. G. and Warner, T. T. (1993). Nonlinear hydrostatic conditional symmetric

instability: implications for numerical weather prediction. *Mon. Wea. Rev.*, **121**, 1821–1833.

Scorer, R. S. (1997). *Dynamics of Meteorology and Climate.* Wiley and Sons.

Shutts, G. J. (1990). Dynamical aspects of the October Storm 1987: a study of a successful fine mesh simulation. *Quart. J. Roy. Meteor. Soc.*, **116**, 1315–1347.

Wallace, J. M. and Hobbs, P. V. (1977). *Atmospheric Science: An Introductory Survey.* Academic Press, New York.

Young, M. V. and Grahame, N. S. (1999). Forecasting the christmas eve storm 1997. *Weather*, **54**, 382 391.

CURRENT JCMM INTERNAL REPORTS

This series of JCMM Internal Reports, initiated in 1993, contains unpublished reports and also versions of articles submitted for publication. The complete set of Internal Reports is available from the National Meteorological Library on loan, if required.

1. **Research strategy and programme**
   K A Browning et al
   January 1993

2. **The GEWEX Cloud System Study (GCSS)**
   GEWEX Cloud System Science Team
   January 1993

3. **Evolution of a mesoscale upper tropospheric vorticity maximum and comma cloud from a cloud-free two dimensional potential vorticity anomaly**
   K A Browning
   January 1993

4. **The global energy and water cycle**
   K A Browning
   July 1993

5. **Structure of a midlatitude cyclone before occlusion**
   K A Browning and N Roberts
   July 1993

6. **Developments in systems and tools for weather forecasting**
   K A Browning and G Szejwach
   July 1993

7. **Diagnostic study of a narrow cold frontal rainband and severe winds associated with a stratospheric intrusion**
   K A Browning and R Reynolds
   August 1993

8. **Survey of perceived priority issues in the parametrizations of cloud-related processes in GCMs**
   K A Browning
   September 1993

9. **The effect of rain on longwave radiation**
   I Dharssi
   September 1993

10. **Cloud microphysical processes - a description of the parametrization used in the large eddy model**
    H Swann
    October 1993

11. **An appreciation of the meteorological research of Ernst Kleinschmidt**
    A J Thorpe
    May 1992

12. **Potential vorticity of flow along the Alps**
    A J Thorpe, H Volkert and Dietrich Heimann
    August 1992

13. **The representation of fronts**
    A J Thorpe
    January 1993

14. **A parametrization scheme for symmetric instability: test for an idealised flow**
C S Chan and A J Thorpe
February 1993

15. **The Fronts 92 Experiment: a Quicklook Atlas**
Edited by T D Hewson
November 1993

16. **Frontal wave stability during moist deformation frontogenesis**
Part 1: Linear wave dynamics
C H Bishop and A J Thorpe
May 1993

17. **Frontal wave stability during moist deformation frontogenesis**
Part 2. The suppression of non-linear wave development
C H Bishop and A J Thorpe
May 1993

18. **Gravity waves in sheared ducts**
S Monserrat and A J Thorpe
October 1993

19. **Potential vorticity and the electrostatics analogy: quasi-geostrophic theory**
C Bishop and A J Thorpe
November 1993

20. **Recent advances in the measurement of precipitation by radar**
A J Illingworth
April 1993

21. **Micro-physique et givrage: cloud microphysics and aircraft icing**
A J Illingworth
May 1993

22. **Differential phase measurements of precipitation**
M Blackman and A J Illingworth
May 1993

23. **Estimation of effective radius of cloud particles from the radar reflectivity**
N I Fox and A J Illingworth
May 1993

24. **A simple method of Dopplerising a pulsed magnetron radar**
A Hua, A J Illingworth and J Eastment
November 1993

25. **Radiation and polar lows**
George C Craig
February 1994

26. **Collected preprints submitted to the International Symposium on the Life Cycles of Extratropical Cyclones; Bergen, Norway, 27 June - 1 July 1994**
April 1994

27. **Convective frontogenesis**
Douglas J Parker and Alan J Thorpe
April 1994

28. **Improved measurement of the ice water content in cirrus using a total water evaporator**
Philip R A Brown and Peter N Francis
April 1994

29. **Mesoscale effects of a dry intrusion within a vigorous cyclone**
K A Browning and B W Golding
April 1994

30. **GEWEX Cloud System Study, Science Plan**
May 1994

31. **Parametrization of momentum transport by convectively generated gravity waves**
R Kershaw
May 1994

32. **Mesoscale Modelling Newsletter No 5**
May 1994

33. **Observations of the mesoscale sub-structure in the cold air of a developing frontal cyclone**
K A Browning, S A Clough, C S A Davitt, N M Roberts and T D Hewson
May 1994

34. **Longwave radiative forcing of a simulated tropical squall line**
Imtiaz Dharssi
July 1994

35. **On the nature of the convective circulation at a kata-cold front**
K A Browning
September 1994

36. **Collective preprints of papers submitted to the COST-75 International Seminar on Advanced Weather Radar Systems, Brussels, 20-23 September 1994**
November 1994

37. **Use of satellite imagery to diagnose events leading to frontal thunderstorms: Parts I and II of a case study**
K A Browning and N M Roberts
November 1994

38. **The role of spaceborne millimetre-wave radar in the global monitoring of ice cloud**
P R A Brown, A J Illingworth, A J Heymsfield, G M McFarquhar, K A Browning and M Gosset
December 1994

39. **Potential vorticity inversion**
Michal Ziemianski
October 1994

40. **Theory of mature tropical cyclones; a comparison between Kleinschmidt (1951) and Emanuel (1986)**
Suzanne L Gray
December 1994

41. **Dispersion and removal of pollutants during the passage of an atmospheric frontal system**
N R Gimson
December 1994

42. **The role of snow sublimation in frontogenesis**
D J Parker and A J Thorpe
December 1994

43. **Potential vorticity and the electrostatics Analogy: Ertel-Rossby formulation**
A J Thorpe and C H Bishop
December 1994

44. **Mesoscale aspect of extratropical cyclones: an observational perspective**
K A Browning
January 1995

45. **A polar low outbreak: evolution and mesoscale structures**
T D Hewson, G C Craig and C Claud
February 1995

46. **Generation of near-surface gusts of deep convection**
K Nakamura and R Kershaw
April 1995

47. **Attribution concepts applied to the Omega Equation**
S A Clough, C S A Davitt and A J Thorpe
June 1995

48. **Parametrization of mixed-phase cloud and precipitation**
Susan P Ballard and M Gerard Hutchinson
June 1995

49. **Short-range forecasting of stratocumulus: initialization prediction**
Susan P Ballard, Simon D Jackson and B Macpherson
June 1995

50. **Contributions of the JCMM/Dept of Meteorology Radar Group to the 27th AMS Radar Meteorology Conference, Vail October 1995**
June 1995

51. **Cold pools in shear**
Douglas J Parker
September 1995

52. **High-resolution analysis of frontal fracture**
K A Browning, S P Ballard and C S A Davitt
September 1995

53. **The albedo of broken cloud fields: calculations using a modified two stream radiation code**
Imtiaz Dharssi and Roy Kershaw
October 1995

54. **Parametrization of momentum transport by convection. I: theory and cloud modelling results**
R Kershaw and D Gregory
November 1995

55. **Variation of frontal structure along a cold front**
K A Browning and N M Roberts
November 1995

56. **Secondary frontal waves**
Douglas Parker
December 1995

57. **Objective fronts**
T D Hewson
March 1996

58. **Mesoscale analysis of the activation of a cold front during cyclogenesis**
K A Browning, N M Roberts and A J Illingworth
June 1996

59. **Investigation of different representations of rain in a 1-d evaporation model**
H Swann
May 1996

60. **Parametrization of diabatic processes in the inversion of the omega-equation**
M Athanassiadou and A J Thorpe
June 1996

61. **The role of the environmental flow in the development of secondary frontal cyclones**
I A Renfrew, A J Thorpe and A Joly
June 1996

62. **Consequences of the geostrophic momentum approximation on barotropic instability**
S Malardel, A J Thorpe and A Joly
June 1996

63. **Contributions to the AMS/RMS Conference on Mesoscale Processes**
Reading, 9-13 September 1996

64. **Vorticity and potential vorticity in stratified flows interacting with an isolated obstacle**
Jorge A Gutiérrez and A J Thorpe
September 1996

65. **Triple point development: two case studies**
Douglas Parker
September 1996

66. **Radar observations of wind-shear splitting within evolving atmospheric Kelvin-Helmholtz billows**
D Chapman and K A Browning
April 1997

67. **Cold frontal structure derived from radar wind profilers**
K A Browning, D Jerrett, J Nash, T Oakley and N M Roberts
May 1997

68. **The dry intrusion and its effect on the frontal, cloud and precipitation structure of extratropical cyclones**
K A Browning - Text of invited special lecture at the Spring Conference
of the Meteorological Society of Japan, University of Tsukuba, 22 May 1997

69. **Met. Office Unified Model data, diagnostics, graphics programs, and other observational data available from the JCMM through the aegis of the Universities Weather Research Network (UWERN).** (Plus supplement)
Peter Panagi and Ed Dicks
June 1997

70. **Contributions of the JCMM/Dept of Meteorology Radar Group to the 28th AMS Radar Meteorology Conference.** Austin, Texas
September 1997

71. **Sensitivity of short-range weather forecasts to local potential vorticity modifications**
Meral Demirtas and Alan Thorpe
July 1997

72. **Objective identification of frontal wave cyclones**
T D Hewson
August 1997

73. **Attribution and its application to mesoscale structure associated with tropopause folds**
A J Thorpe
September 1997

74. **The role of the environmental flow in the development of secondary frontal cyclones**
Ian A Renfrew, Alan J Thorpe and Craig H Bishop
September 1997

75. **Potential vorticity: a short history of its definitions and uses**
Alan J Thorpe and Hans Volkert
September 1997

76. **Superposing semi-geostrophic potential vorticity anomalies**
H R Birkett and A J Thorpe
September 1997

77. **Short period forecasting of catchment-scale precipitation.**
Part 1: the role of Numerical Weather Prediction
M A Pedder, M Haile and A J Thorpe
September 1997

78. **Verification of the tracking technique used in an experimental cloud motion wind inferring system**
Z Wang, K A Browning and G A Kelly
October 1997

79. **A preliminary study of Fourier series analysis for cloud tracking with GOES high temporal resolution images**
Z Wang
October 1997

80. **Analysis of an ex-tropical cyclone after reintensifying as a warm-core extratropical cyclone**
K A Browning, G Vaughan and P Panagi
November 1997

81. **A JCMM overview of FASTEX IOPs**
S A Clough, H W Lean, N M Roberts, H Birkett, J-P Chaboureau, R Dixon, M Griffiths, T D Hewson and A Montani
January 1998

82. **Programs for PV inversion and modification**
Meral Demirtas
December 1997

83. **Release of potential shearing instability in warm frontal zones**
D Chapman and K A Browning
February 1998

84. **The European Cloud-Resolving Modelling Programme (EUCREM)**
Summary Report from the coordinator
P W White
April 1998

85. **A frontal wave database**
T D Hewson
April 1998

86. **Layering observed in dropsoundings from IOP 1 of Fronts 92**
S A Clough
May 1998

87. **Use of wind-shear displays for Doppler radar data**
D Chapman and K A Browning
May 1998

88. **Radar estimates of rainfall rates at the ground in bright band and non-bright band events**
T J Smyth and A J Illingworth
June 1998

89. **Correction for attenuation of radar reflectivity using polarisation data**
T J Smyth and A J Illingworth
June 1998

90. **The effects of convection on chemical reactions and precipitation scavenging**
Neil R Gimson
July 1998

91. **How to use the display program DISP**
Nigel Roberts
August 1998

92. **Conceptual models of cyclogenesis**
Adrian T Semple
August 1998

93. **Observations of oblate hail using dual polarisation radar and implications for hail detection schemes**
T J Smyth, T M Blackman and A J Illingworth
September 1998

94. **The semigeostrophic diagnosis of vertical motion. Part I: Formulation and co-ordinate transformations**
Mike A Pedder and Alan J Thorpe
September 1998

95. **The semigeostrophic diagnosis of vertical motion. Part II: Results for an idealised baroclinic wave life cycle**
Alan J Thorpe and Mike A Pedder
September 1998

96. **Convective destabilisation by a tropopause fold diagnosed using potential vorticity inversion**
Morwenna Griffiths, Alan Thorpe and Keith Browning
October 1998

97. **Forecast skill of the ECMWF model using targeted observations during FASTEX**
A Montani, A J Thorpe, R Buizza and P Unden
October 1998

98. **Observations and model simulations of the FASTEX IOP 16 frontal wave - effects of sublimation**
Sid A Clough, Humphrey W Lean, Nigel M Roberts and Richard M Forbes
December 1998

99. **The application of conceptual models in NWP**
Adrian T Semple
January 1999

100. **Mesoscale analysis of arc rainbands in a dry slot**
K A Browning and N M Roberts
January 1999

101. **Interaction of mesoscale tropopause depressions with a warm-core cyclone: observational and model analyses, and sensitivity to analysis errors**
K A Browning, A J Thorpe, A Montani, D Parsons, M Griffiths, P Panagi and E M Dicks
February 1999

102. **The use of water vapour imagery and PV inversion to adjust initial conditions in NWP**
Sean J Swarbrick
February 1999
This report is no longer available; see Internal Report No.108

103. **Summary notes for a lecture course on Waves in the Atmosphere and Ocean**
A A White
March 1999

104. **Results of a questionnaire on the operational value of conceptual models (CMs) of fronts and cyclones**
N M Roberts & M V Young
July 1999

105. **Contributions to the Poster Session at the 1998 UWERN Annual Science Meeting**
assembled by A A White
August 1999

106. **The objective analysis of dropsonde data from FASTEX**
Richard Forbes, Sid Clough, Mark Dixon, Andy Macallan & Nigel Roberts
January 2000

107. *NWP Technical Report No.302*
Implications for Mesoscale Modelling from a Study of the FASTEX IOP 16 Mid-latitude Cyclone
Richard M Forbes, Humphrey W Lean, Nigel M Roberts and Peter A Clark
March 2000

108. *NWP Technical Report No.291*
The use of water vapour imagery and PV inversion to adjust initial conditions in NWP
Final Project Report
Sean J Swarbrick
September 1999

109. *NWP Technical Report No.294*
A guide to aspects of water vapour imagery interpretation: the significance of dry regions
Nigel M Roberts
January 2000

110. *NWP Technical Report No.300*
The relationship between water vapour imagery and thunderstorms
Nigel M Roberts
February 2000

111. *NWP Technical Report No.293*
Holomorphic structures in hydrodynamical models of nearly geostrophic flow
V N Roubtsov and I Roulstone
January 2000

112. *NWP Technical Report No.301*
Multi-sensor synthesis of the mesoscale structure of a cold-air comma cloud system
K A Browning, P Panagi and E M Dicks
March 2000

113. *NWP Technical Report No.307*
Observations of stratospheric air entering the circulation of a polar low
K A Browning and E M Dicks
May 2000

114. *NWP Technical Report No.309*
Wind profiler – Unified Model comparison statistics
Peter Panagi & Ed Dicks
March 2000

115. *NWP Technical Report No.310*
Towards a similarity theory of moist convective updrafts
Olaf Stiller and George C Craig
May 2000

116. *NWP Technical Report No.312*
The mystery of striated cloud heads in satellite imagery
R S Dixon, K A Browning and G J Shutts
April 2000

Met Office Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
www.metoffice.com